

## HIGH TEMPERATURE ELECTRONICS

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In recent years, the aerospace propulsion and space power communities have acknowledged a growing need for electronic devices that are capable of sustained high-temperature operation. Aeropropulsion applications for high-temperature electronic devices include engine ground test instrumentation such as multiplexers, analog-to-digital converters, and telemetry systems capable of withstanding hot section engine temperatures in excess of 600 °C. Uncooled operation of control and condition monitoring systems in advanced supersonic aircraft would subject the electronics to temperatures in excess of 300 °C. Similarly, engine-mounted integrated electronic sensors could reach temperatures which exceed 500 °C.

In addition to aeronautics, there are many other areas that would benefit from the existence of high-temperature electronic devices. Space applications include power electronic devices for space platforms and satellites. Since power electronics require radiators to shed waste heat, electronic devices that operate at higher temperatures would allow a reduction in radiator size. Terrestrial applications include deep-well drilling instrumentation, high power electronics, and nuclear reactor instrumentation and control.

To meet the needs of the applications mentioned previously, the high-temperature electronics (HTE) program at the Lewis Research Center is developing silicon carbide (SiC) as a high-temperature semiconductor material. Research is focused on developing the crystal growth, growth modeling, characterization, and device fabrication technologies necessary to produce a family of SiC devices.

Interest in SiC has grown dramatically in recent years due to solid advances in the technology. Much research remains to be performed, but SiC appears ready to emerge as a useful semiconductor material.

## High-Temperature Electronics Program

- **Develop the base technology to establish silicon carbide as an advanced, high-temperature semiconductor material.**
  - **Develop a family of silicon carbide integrated electronic sensors and other electronic devices for a variety of high-temperature and high power aerospace applications.**
- **Need for high-temperature electronics, benefits of silicon carbide.**
  - **Growth of electronic-quality silicon carbide.**
  - **Device characteristics.**
  - **Focus of current and future research.**

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The high-temperature electronics (HTE) program is aimed at developing the base technology to establish silicon carbide as a high-temperature semiconductor material. Research is focused on developing the crystal growth, growth modeling, characterization, and device fabrication technologies necessary to produce a family of silicon carbide integrated electronic sensors and other electronic devices. Such devices would find numerous important applications in aerospace propulsion, space power, and high-temperature terrestrial systems.

## **The Need for High-Temperature Electronics**

**Commercial silicon devices are generally available for use up to 125 °C. Silicon technology is limited to a maximum temperature of 300 °C. There is an increasing need for electronics which reliably operate at a sustained temperature of 400 °C or greater.**

### **Aerospace Propulsion Applications**

- **Engine ground-test instrumentation.**
- **Control and condition monitoring systems.**
- **Integrated electronic sensors.**

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On the basis of the inherent solid-state properties of silicon, the maximum temperature at which a silicon device could theoretically operate is 300 °C. Gallium arsenide could theoretically operate at 460 °C, but it is not stable at this temperature. However, there is an increasing need for electronics which operate at sustained temperatures at or above 400 °C. Engine ground-test instrumentation requires multiplexers, analog-to-digital (A/D) converters, and telemetry systems capable of withstanding hot-section temperatures in excess of 600 °C. Uncooled operation of control and condition monitoring systems in advanced supersonic aircraft would subject the electronics to temperatures in excess of 300 °C. Similarly, engine-mounted integrated electronic sensors could reach temperatures which exceed 500 °C. Additionally, for production aircraft applications, component reliability is of prime concern, and the imposed safety margin further increases the required temperature capability of any semiconductor selected for high temperature use.

## Benefits of Silicon Carbide as Semiconductor Material

Property	Benefit
• Wide bandgap energy	• 400-600 °C electronics and radiation hardened devices
• Excellent stability	• Sustained use in hostile environments
• High breakdown field and high thermal conductivity	• Improved power electronics and increased device packing density
• Excellent high-frequency properties	• Superior high-frequency devices
• Processing similarities to Si	• Potential for rapid commercial development

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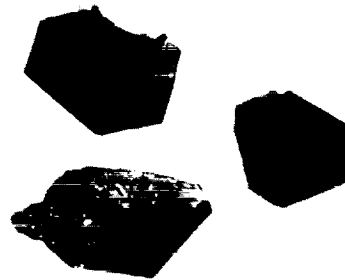
With the same criteria as applied to silicon, silicon carbide could theoretically be employed at temperatures as high as 1200 °C. More reasonable, shorter term goals are to produce electronics capable of first 400 °C, then 600 °C operation. Current silicon carbide (SiC) semiconductor technology is reaching a level where production 400 °C electronics could be achieved in the near-term, while 600 °C electronics will be more of a challenge.

Because of the wide bandgap, and high operating temperature, SiC devices promise to be superior in radiation hardness over those using silicon or gallium arsenide. This material is also characterized by excellent physical and chemical stability, which make it suitable for long-term use in high-temperature, corrosive environments. The combination of the material's high breakdown field and high thermal conductivity provides the potential for improved power system electronics and for increasing the number of devices per unit area. Those properties, which determine the high-frequency characteristics of semiconductors, appear to be excellent for silicon carbide and superior to those of silicon or gallium arsenide. Finally, some similarities to well-established silicon processing techniques exist for SiC and this should aid in promoting its commercial development.

## Silicon Carbide Crystals



Wafer (Cree Research, Inc.)

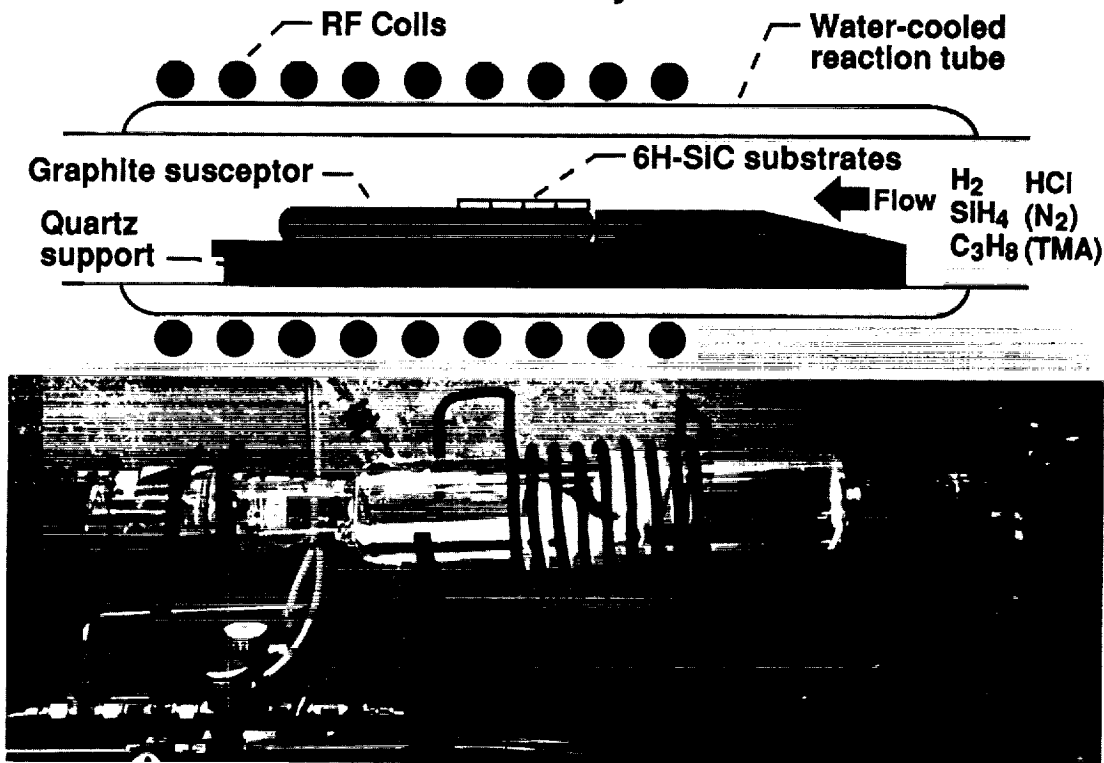


Lely crystals

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Prototype silicon carbide devices were demonstrated above 400 °C as early as 25 years ago, but most research in the U.S. was terminated in the early 1970's because of an inability to produce the large-area, high-quality crystals required for commercial production. Unlike silicon and gallium arsenide, which are grown from a melt, silicon carbide (SiC) has no liquid phase and must be grown from the vapor state by sublimation. As is shown by the Lely process crystals in the photograph, the quality and size of SiC crystals were extremely difficult to control. However, in 1982, researchers at NASA Lewis developed a chemical vapor deposition (CVD) process which permitted the growth of thin, epitaxial films of SiC on standard silicon semiconductor wafers. For this discovery, an I-R 100 award was presented. Through the 1980's, several groups worldwide employed this method to grow SiC, and the work continues today. However, a recent development in SiC crystal growth is having an enormous impact on the research. A SiC research team at North Carolina State University announced the successful implementation of a seeded-growth sublimation method to produce SiC in boule (large cylinder) form. A private company, Cree Research Inc., has developed this process to the point where 1-in. diameter wafers of SiC are now being produced. Westinghouse Electric Corp. has duplicated this capability. The significance of this accomplishment is that SiC crystals can now be used as substrates for SiC epitaxial growth via the CVD processes already developed. The growth of very high quality SiC epitaxial films has now been achieved at NASA Lewis using these substrates.

## SiC Chemical Vapor Deposition Reaction System



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A diagram of the chemical vapor deposition (CVD) reaction system is presented. A silicon or silicon carbide substrate is placed on a radiofrequency-heated graphite susceptor. Rapidly ramping the temperature of the silicon (Si) substrate in the presence of silane (SiH<sub>4</sub>) and propane (C<sub>3</sub>H<sub>8</sub>) in a hydrogen carrier gas produces single-crystal SiC. Depending on the substrate surface preparation employed, and the growth conditions, various crystalline forms of silicon carbide, called polytypes, can be grown. Doping (intentional insertion of the extrinsic carriers) the epitaxial films with electrical impurities to produce *n*-type and *p*-type SiC is vital to the realization of electronic devices. Addition of nitrogen gas to the growth process results in nitrogen incorporation into the SiC lattice. Since nitrogen is a donor impurity in SiC, *n*-type SiC is produced. To produce *p*-type SiC, aluminum has been used as an acceptor impurity. Aluminum is incorporated by adding trimethylaluminum to the growth process gases.

## Chemical Vapor Deposition System

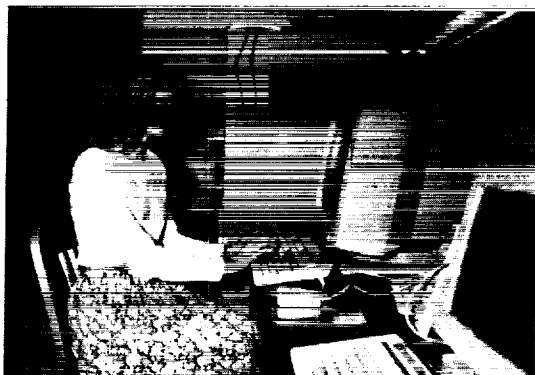


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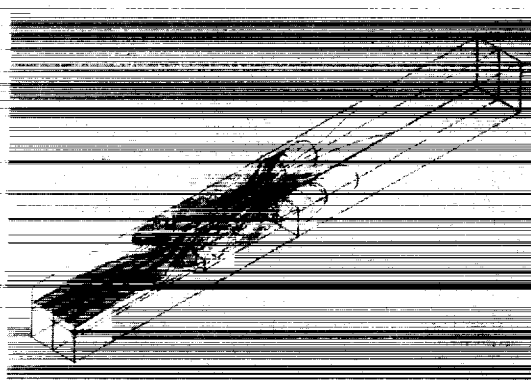
A photograph of the chemical vapor deposition system is shown. The reaction tube and associated plumbing are in the hood (left). The control valves and flow controllers reside in the vented area directly to the right. In the right foreground are the manual and computer control systems. The radiofrequency generator is not shown.

# Chemical Vapor Deposition System Modeling

**Objective: Provide an understanding of the effects of transport phenomena and chemistry on a global scale to improve SiC film quality**



**Modeling station**



**CVD flow modeling**

## **Results/current research**

- **An increase in high quality SiC film growth area resulted from modifying the system susceptor as indicated by flow modeling studies**
- **Current study results will be used to guide CVD reactor scale-up to full wafer growth capability**

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While much empirical data has been generated for the CVD process, it is not well understood from a fundamental scientific standpoint. It is a very complex technique which can be difficult to experimentally optimize and particularly difficult if one is faced with predicting the effects of needed system modifications. As a result, the HTE program has vigorously pursued studies in CVD reactor modeling. Current research involves attempts to model both transport phenomena and chemistry in the reaction chamber. The results to date have provided solid guidance on system improvements and, we believe, hold much promise for the future in advancing SiC CVD growth technology.

# Silicon Carbide Crystal Characterization and Processing



**Crystal characterization techniques**



**Crystal processing techniques**

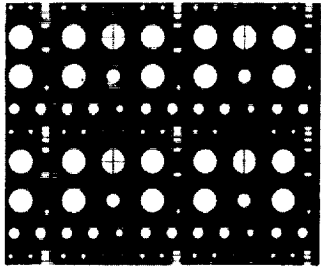
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In addition to SiC crystal growth and growth modeling, a variety of crystal characterization and processing techniques are employed and studied in the HTE program. Electrical, chemical, and morphological characterization of samples is key to evaluating progress in the area and guides crystal processing and growth efforts. Selected examples of facilities are shown here. Clockwise from top left they are optical microscopy, scanning electron microscopy, oxidation, and crystal dicing. The Lewis program also sponsors several excellent characterization efforts at Case Western Reserve University, the University of Pittsburgh, and Howard University.

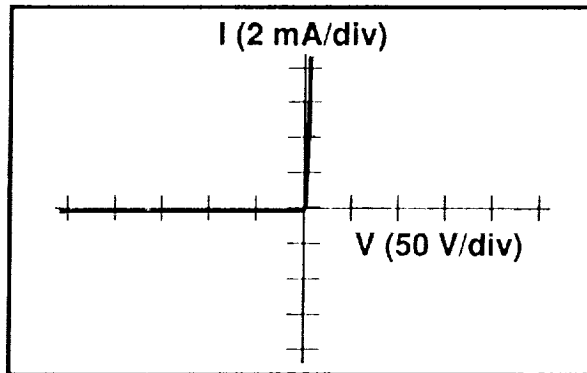
## Silicon Carbide Junction Diode

**Accomplishment:** Highest reported operational temperature (600 °C) for any p-n junction diode device. Significantly improved characteristics above 400 °C. Demonstrates high quality 6H-SiC epitaxial film growth processes.

Diode array



I-V Characteristics at 600 °C



**Benefits:** Silicon carbide diodes (p-n junctions) are basic building blocks from which all future silicon carbide electronic devices will be developed

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The availability of SiC substrates, combined with progress in processing and growth, has permitted NASA Lewis to place increasing emphasis on device fabrication. In-house research is pursuing the fabrication of grown junction diodes, metal-insulator-semiconductor field effect transistors (MISFET's), and metal-oxide-semiconductor field-effect transistors (MOSFET's). Recent results have been dramatic.

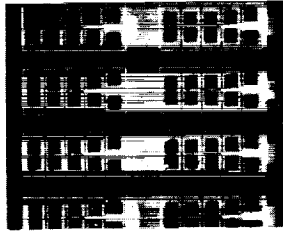
The first high-temperature prototype SiC device fabricated was a *p-n* junction diode. The junction structure was produced by first growing a nitrogen-doped *n*-type 6H-SiC film followed by an aluminum-doped *p*-type film. Photolithography and reactive ion etching were used to fabricate an array of mesa diodes. After passivating the junction boundary with silicon dioxide, metal contacts were then applied to the *p* and *n* regions.

A typical current-voltage (*I-V*) curve for one of the SiC grown-junction diodes is shown above. The function of a diode is to allow current to pass in one direction (the forward direction), but not in the opposite (reverse) direction. Hence, an ideal *I-V* curve would be nearly vertical in the forward direction, and nearly horizontal in the reverse direction. As is seen in the *I-V* curve, the diode exhibits excellent characteristics at 600 °C, the highest temperature measured. This is a significant result because the diode (i.e., *p-n* junction) is a basic building block for electronic devices.

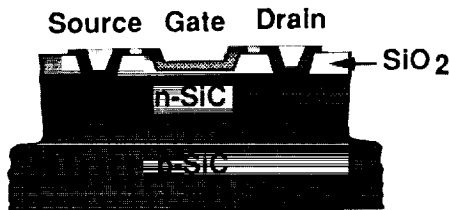
## Silicon Carbide MOSFET

**Accomplishment:** A depletion-mode silicon carbide MOSFET has been developed and successfully demonstrated at an operational temperature of 500 °C.

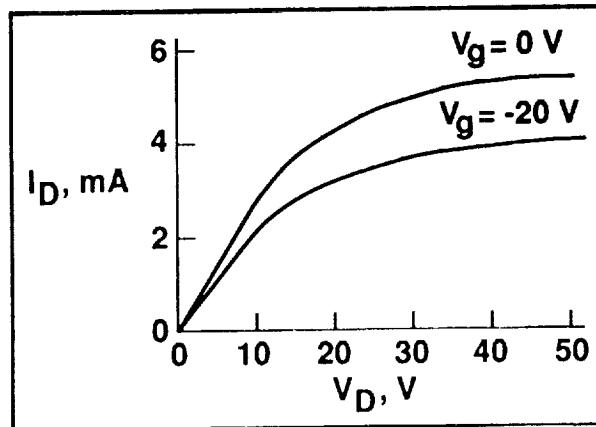
**MOSFET array**



**SiC MOSFET structure**



**I-V Characteristics at 500 °C**



**Benefits:** Silicon carbide MOSFET's (switches) provide the most basic active electronic device from which integrated circuits can be developed.

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Another prototype SiC device fabricated at NASA Lewis was a metal-oxide-semiconductor field-effect-transistor (MOSFET). The MOSFET structure is shown above. For this device, the sequence of SiC films grown on the SiC substrate consisted of (1) an *n*-type buffer layer (not shown), (2) a *p*-type isolation layer, and (3) a 0.7- $\mu$ m-thick *n*-type channel layer. An array of MOSFET's were then fabricated from this structure using many additional steps that included photolithography, oxidation, and metallization.

In an FET structure, the current flow is controlled by applying a voltage to the gate electrode. For an *n*-channel FET, a negative voltage applied to the gate will deplete the channel of electrons and thus "pinch-off" the current flow. In this manner, an FET resembles a switch. The switch is turned on and off by the application of the gate voltage. The *I*-*V* characteristics of the MOSFET at 500 °C are presented below. Although the electrical characteristics of the FET are not ideal, the achievement of transistor *I*-*V* characteristics at 500 °C is an extremely important starting point, since the FET provides the most basic active electronic device that can be employed to develop integrated circuits.

## **Focus of Current and Future Lewis High-Temperature Electronics Research**

### **Current:**

- **Fundamental studies of SiC properties.**
- **CVD research to improve crystal quality.**
- **Detailed crystal characterization studies.**
- **CVD modeling studies.**
- **Device metallization research.**
- **Discrete device fabrication research.**

### **Future:**

- **Continue all current research efforts.**
- **Perform research in passivation, wire attachment, and packaging.**
- **Demonstrate simple integrated circuit technology.**
- **Demonstrate integrated electronic sensor technology.**

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Current and future HTE research areas are outlined. The program scope is quite diverse and addresses a wide range of fundamental and applied areas critical to the future success of SiC. The HTE Group is heavily involved in a growing network of government, industrial, and academic programs in SiC. We will continue to participate in collaborative efforts to advance this technology as rapidly as is possible.

Future research will expand into more applied areas which will be addressed through a combination of in-house, collaborative, and sponsored research.

## CONCLUDING REMARKS

Ultimately, the goal of the NASA Lewis High Temperature Electronics Program is to develop SiC integrated circuits and monolithic sensors with compensating and signal conditioning electronics integrated into the sensor structure. Electronic devices and sensors that are capable of operating at elevated temperatures eliminate or substantially reduce the amount of cooling that is required. Other payoffs of high temperature integrated sensors include reduced cabling and shielding requirements and the development of distributed control architectures, e.g., smart actuators.

Silicon carbide semiconductor technology was just a promise for many years, but has accelerated rapidly over the last several years. The devices fabricated at NASA Lewis and elsewhere demonstrate that excellent performance can be achieved. We want to emphasize that much development and optimization remain. However, the payoffs for success are tremendous. We believe that SiC can be an enabling electronic technology for many of the ambitious plans that mankind has for the Earth, air, and space.

